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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) (6) Heat stress, work function and physiological heat exposure limits in man.	5. TYPE OF REPORT & PERIOD COVERED (9) Medical Research Progress Repts.
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) A. R. DASLER Ph. D.	8. CONTRACT OR GRANT NUMBER(s) (16) F51524
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Medical Research Institute Bethesda, Maryland 20014	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (17) MF51524023 1005 Report No. 1
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Medical Research and Development Command Bethesda, Maryland 20014	12. REPORT DATE (11) Feb[redacted]977
	13. [redacted] 23 (12) 32p
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Bureau of Medicine and Surgery Department of the Navy Washington, D. C. 20372	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release and sale; distribution unlimited.

DDC

FEB 16 1978

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

In Thermal Analysis-Human Comfort-Indoor Environments. Proceedings of a Symposium held at the National Bureau of Standards, Gaithersburg, Maryland. Washington, NBS, 1977. pp.65-92

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Heat Stress; Exposure Limits; Thermal Analysis

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Various operational trials using tolerance criteria available in the literature revealed that predictions of physiological exposure limits were rarely compatible with the observed status of men in a wide range of heat stress and work conditions. Computer integration of laboratory and industrial-type data led to establishing a comprehensive set of physiological criteria for tolerance limits appropriate to man at work within time-weighted-mean (t_{wm}) metabolic rates from 76-126 kcal/(m^2.hr) [88.4 - 146.5 W.m^{-2}]. These criteria and work rates were integrated with industrial-type heat stress conditions over the t_{wm} WBGT Index

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S/N 0102-LF-014-6601

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range of 82 - 130°F[27.8 - 54.4°C]; which resulted in developing the Physiological Heat Exposure Limits (PHEL) concept. Several electronic heat stress monitor-devices were evaluated and employed in determining environmental conditions. In all laboratory and field studies the dry- and wet-bulb and globe temperatures were recorded. Physiological data were obtained at the same time as the environmental data. Although the physiological data obtained in the laboratory were much more broad in scope than in the field settings, the field approach included physical characteristics of the subjects, body temperatures (skin and rectal), cardiovascular (heart rates and blood pressures) and metabolic-respiratory (O_2 consumption, respiratory minute volume and respiration rates) data during rest and performance of dynamic work; sweat rates were determined by body weight changes when feasible in the non-laboratory trials. Coefficients for physiological factors in the heat stress and strain equations were automatically adjusted for physiological changes determined in the actual situations. Comparison of over 200 sets of environmental and physiological data supported the PHEL concept and permitted more definitive identification of material areas requiring corrective engineering actions in the industrial-type settings. Corrective engineering actions based upon results of the data analyses have permitted nearly a sixfold increase of the maximum physiological exposure times; simultaneously, the estimated cardiovascular reserve increased from 15% to as much as 85% during routine work.

NBS SPECIAL PUBLICATION 491

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Thermal Analysis — Human Comfort — Indoor Environments

Thermal Analysis—Human Comfort—Indoor Environments

Proceedings of a Symposium Held at the
National Bureau of Standards
Gaithersburg, Maryland
February 11, 1977

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Sponsored by:

The National Bureau of Standards
Department of Commerce
Washington, D.C. 20234

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Acting Director

Issued September 1977

HEAT STRESS, WORK FUNCTION AND PHYSIOLOGICAL HEAT EXPOSURE LIMITS IN MAN

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Abstract

Various operational trials using tolerance criteria available in the literature revealed that predictions of physiological exposure limits were rarely compatible with the observed status of men in a wide range of heat stress and work conditions. Computer integration of laboratory and industrial-type data led to establishing a comprehensive set of physiological criteria for tolerance limits appropriate to man at work within time-weighted-mean (t_{wm}) metabolic rates, from 76 - 126 kcal/(m²·hr) [88.4 - 146.5 W·m^{-2}]. These criteria and work rates were integrated with industrial-type heat stress conditions, over the t_{wm} WBGT Index range of 82 - 130°F [27.8 - 54.4°C]; which resulted in developing the Physiological Heat Exposure Limits (PHEL) concept. Several electronic heat stress monitor-devices were evaluated and employed in determining environmental conditions. In all laboratory and field studies the dry- and wet-bulb and globe temperatures were recorded. Physiological data were obtained at the same time as the environmental data. Although the physiological data obtained in the laboratory were much more broad in scope than in the field settings, the field approach included physical characteristics of the subjects, body temperatures (skin and rectal), cardiovascular (heart rates and blood pressures) and metabolic-respiratory (O_2 consumption, respiratory minute volume and respiration rates) data during rest and performance of dynamic work; sweat rates were determined by body weight changes when feasible in the non-laboratory trials. Coefficients for physiological factors in the heat stress and strain equations were automatically adjusted for physiological changes determined in the actual situations. Comparison of over 200 sets of environmental and physiological data supported the PHEL concept and permitted more definitive identification of material areas requiring corrective engineering actions in the industrial-type settings. Corrective engineering actions based upon results of the data analyses have permitted nearly a sixfold increase of the maximum physiological exposure times; simultaneously, the estimated cardiovascular reserve increased from 15% to as much as 85% during routine work.

Key Words: Heat Stress, Exposure Limits, Thermal Analysis

Introduction

Heat stress and strain have a profound impact upon man and industry. Regardless of the specific causes, the immediate consequences of uncompensated heat stress upon man are observed as a major loss of man's performance efficiency and the loss of work productivity time. It is generally known that excessive heat stress exposures lead to a progressive loss of performance capability, lowered resistance to some stresses, and low retention of personnel.

Establishment of the Occupational Safety and Health Act of 1970 was a significant

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Supported by Naval Medical Research & Development Command, Navy Department, Research Subtask MF51.524.023-1005.

stimulus for the civilian community to recognize the need for much greater awareness and initiation of corrective actions relative to heat stress problems. Lengthy deliberations were held by the Steering Committee for the Occupational Safety and Health Administration (OSHA). Numerous testimonies were given and a number of drafts of a proposed U.S. Federal Heat Exposure Standard were submitted to OSHA. The Steering Committee's final document was submitted on 11 January 1974. The main intent of the proposed Standard document was to provide guidelines as to when sound health practices should be introduced to protect workers. In the final document it was clear that questions regarding heat tolerance limits remained unanswered. In other words, the proposed Standard was to serve as a basis whereby industry should begin to institute sound health practices as the thermal environment and rate of work began to impose strain within workers; conversely, the document did not truly address tolerance limits where exposures and work rates would have to be terminated. A number of pitfalls in attempting to establish a more encompassing heat exposure standard were recently presented,[1] and it is very likely that many of the limitations in the proposed standard have had a major impact upon the absence of a currently OSHA approved set of heat exposure guidelines in this country.

Progress in identifying and combatting the adverse effects of heat stress and attempting to minimize the physiological strain in man have been extremely varied over the years. It is readily apparent that the total problem is far more complex when research is confronted with the real world of multiple combinations of physical factors in the environment and the physiological capabilities of man, whether it is a civilian or military situation. The majority of prior efforts were limited to studying only a few variables simultaneously. The technology-of-the-day did not permit development of concise solutions to involved questions; the scope of generally used physiological variables was extremely narrow; and, occasionally some past research was influenced by subjective information. Exploitation of modern technology has increased the ability to integrate numerous research findings and to improve bilateral cross-overs between laboratory and field efforts. It was through the use of the practical state-of-the-art technology today that the questions regarding heat stress, work function and physiological heat exposure limits were examined. The product, in terms of what can be assessed objectively at this time, has been the demonstration that it is feasible to dramatically reduce high heat stress levels and obtain a marked improvement in physiological performance.

Physiological Criteria of Heat Tolerance in Man

Studies of man's capacity to endure heat stress, or heat tolerance as used herein, have utilized a wide range of upper limits for the same physiological parameters. The conventional physiological criteria of heat tolerance have been associated with a range of heart rate (HR) values from 150 - >200 beats·min^{-1}, rectal temperature (T_{re}) from 38.0 - 40.8°C, and sweat rates (SR) to 3.5 liters·hr^{-1}.[2-13] Furthermore, there has been the "too late" approach of allowing exposures to continue until personnel demonstrate imminent collapse or an overt illness.[9,10]

It has been shown that HR, by itself, is a poor predictor of cardiovascular limits when dealing with various ages of workers, rates of work, and states of physical conditioning and acclimatization.[2,14-16] On a sound physiological basis it is not surprising that a HR limit cannot be well-defined as there are numerous offsetting cardiovascular factors which are not illustrated by HR alone.[17] In occupational situations the sole use of HR may be of little significance relative to heat tolerance under a variety of conditions;[10,18-20] HR may be altered by the influence of items such as sodium chloride,[21] or may be misleading in comparison with other changes within the cardiovascular system.[15,22] On the other hand, T_{re} is subject to various interpretations, dependent upon the rates of change,[11,12,23] and the dynamics of other internal body temperatures are such that in transient states T_{re} is the least reliable of the internal body temperatures to depict the more meaningful thermal status of man.[10,12,23] Also, the use of SR must be done with caution as there is evidence that SR's are subject to decrease in comparison with high SR's found early in the total heat acclimatization profile,[4,24] and SR's are markedly reduced with varying amounts of sodium chloride ingestion.[21]

Driven by a basic common sense question regarding what are tolerance limits to heat stress over a variety of general work tasks, and an urgent need for a simplified method which employs factors essential for practical engineering actions, a review of physiological data from over 160 experiments resulted in Table 1. Application of Table 1 required at least two objectives to be reached in order to define physiological heat exposure limits within man; the most appropriate for laboratory and field studies are indicated by "*" of "†" respectively.

Table 1

Improved Physiological Heat Exposure Limits Criteria

I. At Any Time During An Exposure:		
	Heart Rate	>180 beats·min^{-1}
*†	Rectal Temp.	≧39.0°C or ≧1.6°C·hr^{-1}
*	Tympanic Temp.	≧39.5°C or ≧3.5°C·hr^{-1}
*	Esophageal Temp.	≧40.0°C or ≧4.4°C·hr^{-1}
*†	Total Vascular Resistance	≦20% of Control value
	<u>or</u>	
*†	Cardiovascular Reserve[15,22]	0%
	Mental	Disorientation
II. During Sustained Physical Work:		
*†	Systolic Blood Pressure	≧40 mm Hg decrease within 3.5 min. interval
*	Electrocardiogram	R-wave height ≦1 mm of T-wave (using Lead I or Transthoracic) or T-wave inversion
	Korotkoff Sound Intensity	>3-fold increase from Control value
	Ventilation Equivalent	≧47% increase from Control value
	Ratio of Oxygen Removal	≧33% decrease from Control value
	Mental	Onset of euphoria <u>immediately</u> post-irritable
III. Recovery:		
*†	Total Vascular Resistance	<80% of Control value within 20 min. post-exposure
*†	Cardiovascular Reserve	<75% within 20 minutes post-exposure
	Heart Sound Intensities	Sounds I and II remain >3-fold higher than Control even though Heart Rate back to Control level
	Creatinine Phosphokinase	Blood level >1000 units 24-hours post-exposure

* These factors most common in controlled laboratory experiments.

† These factors most common in field experiments where monitoring is less extensive than in laboratory experiments.

Selection of a Simplified Index of Environmental Heat Stress

Earlier experiments in high temperature situations illustrated the difficulties in using available heat stress indices to scale short to long exposure times for men performing a range of routine tasks in industrial-type environments.[7,8,18-20,26] As the U.S. Navy Psychrometric Chart for High Temperature Habitability Limits (NAVSHIPS 4767) had a potential of application, a series of experiments were conducted to examine the validity of the NAVSHIPS Chart for exposures from 15 minutes to 6 hours. Results of the study clearly indicated that the NAVSHIPS Chart was able to provide reasonable agreement with heat tolerance in the so-called "4-hour" and "3-hour" zones, as long as no radiant heat was present and the metabolic rate (MR) was between 55 - 94 $W \cdot m^{-2}$. However, when radiant heat was present there was virtually no agreement with the "4-hour" and "3-hour" zones, and absolutely no agreement with any time zones of less than three hours. Careful examination of the original Bureau of Ships files indicated that the limits for less than three hours, in the proposed but unissued Chart, were based upon the original coefficients of the Belding and Hatch Heat Stress Index (HSI)[27] and that men were dressed only in shorts, socks and shoes; whereas, the "3-" and "4-hour" zones were very wide and were based upon data from men normally clothed. Obviously, the NAVSHIPS 4767 Psychrometric Chart for High Temperature Habitability Limits was unsatisfactory in dealing with combinations of radiant heat environments, was not sufficiently specific even in the absence of radiant heat for short exposure time, required a broader range of MR and should have been consistent with men wearing normal working clothes throughout delineated zones.

The HSI, with revised Fort Knox coefficients, was a likely candidate for selection as it developed the rational concepts of evaporation required to maintain heat balance (E_{req}) and maximum evaporative capacity (E_{max}) in order to obtain the HSI (See Appendix). Unfortunately, even the new nomograms of McKarns and Brief[28] to estimate E_{req}, E_{max} and HSI are much more complicated than a simplified chart for lay usage. Furthermore, using the improved coefficients and making corrections for actual skin temperatures, numerous calculations of the HSI revealed that the HSI values were either negative, implying mild cold stress when in reality there was high heat stress, or the values were far beyond the upper limit of 100. In separating out the factors within the HSI that may have been subject to further modifications, it was determined that when the partial vapor pressure (P_W partial) of the air exceeded the corrected vapor pressure at the skin the value for E_{max} became negative; in other words, a negative E_{max} in high heat stress denoted that at the higher P_W partial of the air, water would condense on the skin of man. These results also meant that the HSI concept was limited, in its current scaling terms, to environmental conditions where evaporative cooling (compensated heat stress) was present. Rescaling of the HSI was considered unwarranted to fit environmental conditions of uncompensated heat stress and tolerance times of less than 8-hour exposures. (Data relative to these negative and greater than 100 values are given later in this text.)

Selection of the Prescriptive Zone (PZ)[2,29] relative to physiological heat tolerance and the physiological heat exposure limits criteria, as given in Table 1, was not appropriate. By definition, the PZ is based upon 95% of an average population not exceeding a body temperature of 38.0°C. The PZ concept emphasizes the need for a nearly steady level of equilibrium in a wide range of climates. Above the upper limits of the PZ an increase in heat stress would result in a disportionate increase in cardiovascular strain unless T_{max} increased beyond 38.0°C. As indicated previously,[7,8,10-12,18-20,26] heat tolerance limits rarely can be defined by internal body temperatures as low as 38.0°C; tolerance limits must be judged by objective criteria which truly reflect the upper points (which are limits) rather than the points of departure from equilibrium. Data comparing "1-hour" and "30-minute" "heat tolerance" using the PZ versus HSI and other indices of heat stress are discussed later in this text.

Review of information on the Wet-Bulb Globe Temperature (WBGT) Index indicated that there were no less than six WBGT equations used in both theoretical and practical situations. Furthermore, reports of Yaglou et. al.,[30] and Yaglou and Minard,[31] did not specify which WBGT equation must be applied indoors. Although usage of $WBGT_a$* for outdoors and $WBGT_b$** for indoors has been widely referenced back to these reports, there was information [32-33] that $WBGT_c$*** was applicable indoors with varying radiant heat levels and was the significant form of WBGT in establishing standard criteria for heat tolerance limits. This latter approach utilizes the integration of time-weighted-mean (t_{wm}) metabolic rates (MR) and t_{wm} $WBGT_c$ with scaling for physiological heat tolerance limits, as given in Table 1, to permit practical utilization of essential environmental factors for physiological tolerance limits, corrective engineering actions and routine surveillance of work areas in industrial-type situations.

Physiological Heat Exposure Limits (PHEL) Chart

Curve fitting of radiant heat research data obtained by the Heat Stress Division, Naval Medical Research Institute (NMRI), revealed that the best fit curves were power regression relationships (r's = -0.985 and -0.998) between t_{wm} MR's of men in normal work clothes, t_{wm} $WBGT_c$ and exposure time limits when the physiological heat exposure limits criteria (Table 1) were met but not exceeded. On an initial basis there were two t_{wm} MR's (88.8 and 111.7 $W \cdot m^{-2}$) and the majority of the 70 sets of data from 15 subjects for each t_{wm} MR were within the t_{wm} WBGT's from 31.1 - 36.7°C. At approximately the same time Royal Navy researchers[8] combined $WBGT_d$**** with a continuous MR of about 170 $W \cdot m^{-2}$, but without the presence of radiant heat. Results of combining three phases of the Royal Navy effort included a total of 87 subjects, 440 sets of observations, and $WBGT_d$ from 32.1 - 53.9°C. Replotting the Royal Navy data revealed that again the best fit curve was described by a power regression (r = -0.983). One major difference between the NMRI research and that of the Royal Navy was that in the NMRI studies exposures were terminated in accordance with the criteria associated with Table 1, whereas, the Royal Navy researchers terminated exposures at the point of imminent collapse or overt illnesses. Another major difference was that the Royal Navy studies were based upon continuous work at a much higher MR than in the t_{wm} MR method used by the Heat Stress Division of NMRI. The Royal Navy goal was predominately directed to problem situations where emergency work would have to be performed continuously at a very high rate of energy expenditure. The goal within the U.S. Navy was directed to a broader spectrum of exposure times (up to six hours) with t_{wm} MR and t_{wm} WBGT values representing a more normal range of environmental and physical work conditions encountered in hot, industrial-type civilian and military situations alike. Noise levels in both the NMRI and Royal Navy studies were maintained at 90 dbA. In NMRI trials away from the laboratory the subjects were required to wear standard stock hearing protection devices when the noise levels exceeded 90 dbA.

Research was continued by the Heat Stress Division, NMRI, and in September 1971 the Navy established the <u>Physiological Exposure Limits</u> (PEL) Chart for use in high temperature environments. It could be said at that time that the PEL Chart permitted determination of the maximum physiological exposure limits, which if not exceeded would permit reversibility of the physiological strain without detectable harm provided rest was allowed in a cool environment. The acronym PEL came into general usage within the Navy[35] until identical acronyms also appeared. In 1973 the Environmental Protective Agency initiated a series of <u>Public Exposure Limits</u> (PEL) covering a broad scope of circumstances which did not include heat stress; furthermore, the National Institute of Occupational Safety and Health (NIOSH) published <u>Permissible Exposure Limits</u> (PEL) in September 1973.[9] In order to avoid confusion in referring to the three identical acronyms, the Navy, in November 1973, adopted the more appropriate title <u>Physiological Heat Exposure Limits</u> (PHEL).[36] The PHEL Chart,

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* $WBGT_a = [(0.1\ T_{db}) + (0.7\ T_{wb\ natural}) + (0.2\ T_g)]$

** $WBGT_b = [(0.7\ T_{wb\ natural}) + (0.3\ T_g)]$

*** $WBGT_c = [(0.1\ T_{db\ shielded}) + (0.7\ T_{wb\ psychrometric}) + (0.2\ T_g)]$

**** $WBGT_d = [(0.7\ T_{wb}) + (0.3\ T_{db})]$

as of 1973, consisted of the previous U.S. Navy PEL curves of 1971 with an additional curve for t_{wm} MR (146.5 $W \cdot m^{-2}$) and extension of the t_{wm} WBGT range to 51.7°C for all three curves. Clearly there is a difference between the U.S. Navy PEL or PHEL Charts and the NIOSH PEL concept; it must be recognized that heat strain will be readily apparent with the U.S. Navy PEL or PHEL when physiological heat exposure limits are reached, but the strain will be reversible if the limits are not exceeded. On the other hand the NIOSH PEL was designed to restrict deep body temperature rises to a maximum of 38°C.

Following the original research design of six equal increments of t_{wm} MR from "76 - 126 kcal/($m^2 \cdot hr$)" [now in equivalent metric units of 88.4 - 146.5 $W \cdot m^{-2}$] the PHEL Chart development continued by obtaining exposure limit curves for 100.0, 123.3 and 134.9 $W \cdot m^{-2}$. The number of subjects, number of observations and other pertinent information regarding each curve are summarized in Table 2 below, with equations for the respective PHEL curves given in the Stress/Strain Evaluation Program (STEP-M2) Abbreviated in the Appendix. As indicated previously, the t_{wm} WBGT range was 31.1 - 51.7°C.

Table 2

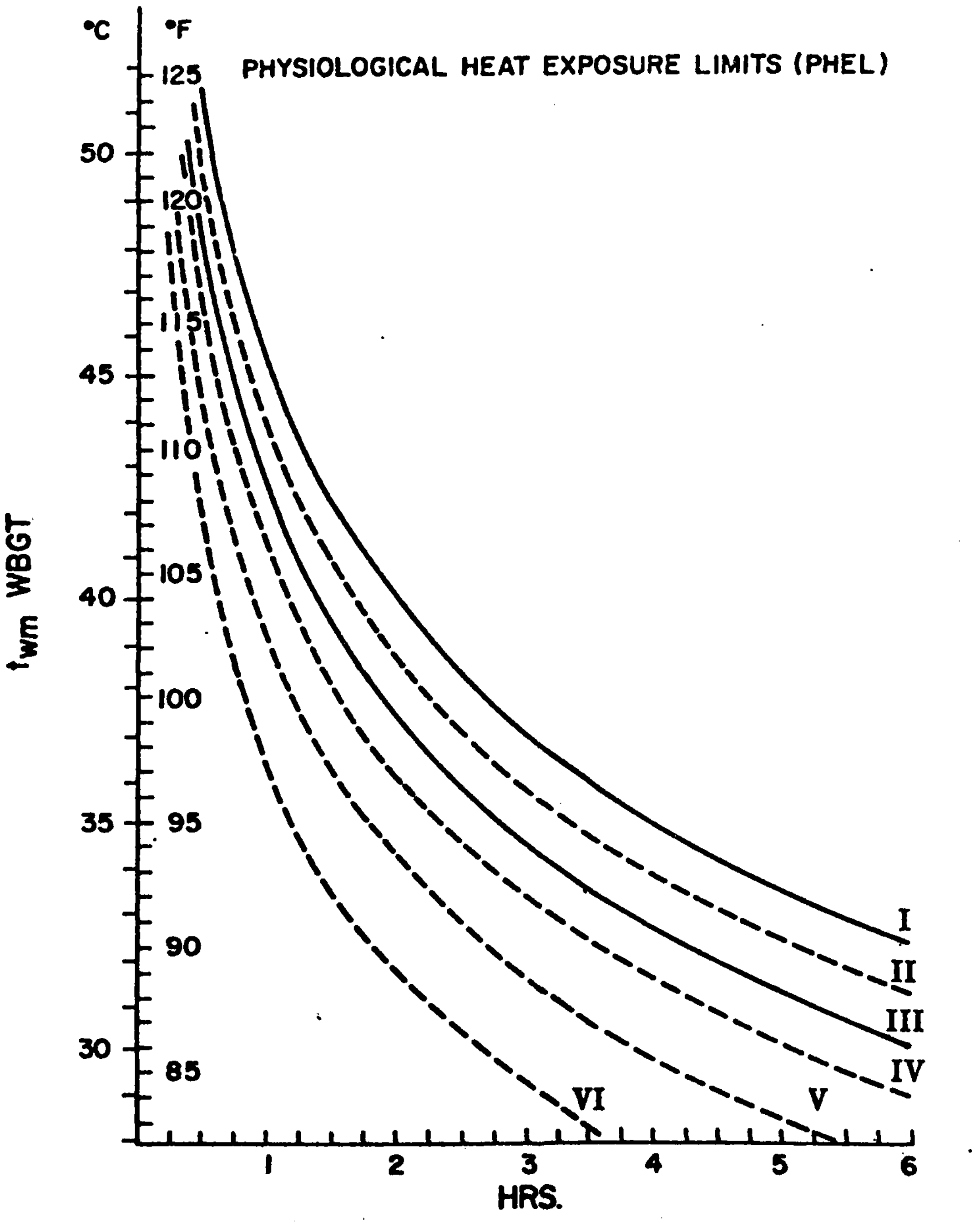
t_{wm} MR	Laboratory Data			Field Data		
($W \cdot m^{-2}$)	No. Subj.	No. Obser.	Power Reg. r	No. Subj.	No. Obser.	Power Reg. r
88.4	32	147	-0.997 *(t = 155.1063)	18	66	-0.995 *(t = 79.6997)
100.0	26	132	-0.998 *(t = 180.0070)	16	52	-0.994 *(t = 64.2589)
111.7	28	137	-0.997 *(t = 149.6623)	18	57	-0.992 *(t = 58.2778)
123.3	25	128	-0.997 *(t = 144.5875)	15	48	-0.993 *(t = 57.0198)
134.9	17	67	-0.987 *(t = 49.3516)	7	20	-0.978 *(t = 19.8907)
146.5	11	46	-0.989 *(t = 44.3516)	5	12	-0.975 *(t = 13.8756)

* t statistics from correlation coefficients, using Hewlett-Packard HP-65 STAT 2-16A transposed for Hewlett-Packard HP-67/97; df = $n_{obser.} - 2$; all t values significant at $p < 0.0001$. Ages of subjects from 19 - 43 years; all subjects health classified as "fit for duty" and each subject experienced in work tasks performed at the t_{wm} MR's.

Utilization of all of the data resulted in the equation $PHEL_{specific}$ given in the Appendix (STEP-M2 Section) for t_{wm} MR's 88.4 - 146.5 $W \cdot m^{-2}$ and t_{wm} WBGT's 31.1 - 51.7°C. Comparing $PHEL_{specific}$ exposure times with the "Safe Exposure Times" given by Bell et. al.[8] indicated that the upper and lower 99% confidence limits of $PHEL_{specific}$ are safe for >95% of the population of subjects; for >99% of the population the lower 99% confidence limits from $PHEL_{specific}$ were safe, but the upper 99% confidence limits exceeded the classification of "safe".

Figure 1 is the PHEL Chart as developed for operational usage and released in the revision of Chapter 3 (Ventilation and Thermal Stress Ashore and Afloat) of the Manual of Naval Preventive Medicine.[37] However, for practical situations which do not need all six of the PHEL curves, an abbreviated PHEL Chart was issued[38] which contains only PHEL curves I ("A"), III ("B") and VI ("C"); the abbreviated PHEL Chart is also given in the Manual of Naval Preventive Medicine.[37]

Figure 1



Curve I ("A") for t_{wm} MR 88.5 $W \cdot m^{-2}$; Curve II for t_{wm} MR 100.0 $W \cdot m^{-2}$; Curve III ("B") for t_{wm} MR 111.7 $W \cdot m^{-2}$; Curve IV for t_{wm} MR 123.3 $W \cdot m^{-2}$; Curve V for t_{wm} MR 134.9 $W \cdot m^{-2}$; and, Curve VI ("C") for t_{wm} MR 146.5 $W \cdot m^{-2}$.

Statistical comparison of adjacent PHEL curves I - IV, within the t_{wm} WBGT range of 35 - 45°C, are presented in Table 3. Paired data from field trials show that the adjacent PHEL curves, based upon the physiological heat tolerance criteria from Table 1, are significantly different.

Table 3

Statistics	Comparison Of Adjacent PHEL Curves		
	I vs. II	II vs. III	III vs. IV
Paired t	10.0489	7.9242	6.4916
df	33	18	19
p	< 0.0001	< 0.0001	< 0.0001

The series of intermittent work-rest cycles in Table 4 demonstrate the utility of the PHEL Chart within the steady state oxygen consumption versus physical activity descriptions given in the ASHRAE Handbook of Fundamentals.[39] In contrast with the intermittent work-rest limits suggested by Esso Research & Engineering Co.,[40] a limited number of calculations using $PHEL_{specific}$ for light and moderate work showed that the large percent differences between the Esso approach and PHEL are related to the more conservative physiological limits criteria used by Esso compared to the criteria limits in Table 1 of this text.

Table 4

PHEL Curves For Intermittent Work-Rest *

Physical Activity **	Work O_2 Consump. ($L \cdot min^{-1}$)	No. Minutes Work/No. Minutes Rest				
		10/50	20/40	30/30	40/20	50/10
Standing	0.50	---	---	---	---	I
Average Light Work	0.75	---	I	II	III	IV
Upper Light to Lower Moderate Work	1.00	---	II	IV	VI	---
Average Moderate Work	1.25	I	III	VI	---	---
Upper Moderate to Lower Heavy Work	1.50	II	V	---	---	---
Average Heavy Work	1.75	II	VI	---	---	---
Upper Heavy to Lower Very Heavy Work	2.00	III	---	---	---	---
Average Very Heavy Work	2.25	IV	---	---	---	---
Upper Very Heavy Work	2.50	IV	---	---	---	---

* Use of this approach involves the selection of the closest PHEL curve representing the t_{wm} MR appropriate to the work-rest cycle at the specified level of physical activity. An alternate approach is to use $PHEL_{specific}$ as given in STEP-M2 of the Appendix.

** As indicated in Table 5 of ASHRAE Handbook of Fundamentals.[39]

Another important set of comparisons with the PHEL concept is given in Table 5. As WBGT increased 8 - 11 percent and MR remained the same it was expected that heat tolerance times would decrease and cardiovascular strain would increase, or cardiovascular reserve would decrease. In Table 5, due to changing the environmental temperatures, WBGT increased within each set of physical activities, the PHEL decreased and estimated cardiovascular reserve[15,22] (CVR) decreased; therefore, the stress increased and the strain also increased. However, the work of Nishi and Gagge[41] to predict both comfort and heat tolerance through use of the PZ does not agree with the above expectations. Although a deep body temperature rise limit of 38.0°C for the PZ may be practical for instituting sound health practices of a preventive nature (such as providing drinking water, etc.), as environmental temperatures increase (like that in the proposed OSHA Heat Standard), the limit of 38.0°C again does not define heat tolerance limits of man. Furthermore, as previously noted relative to the HSI, a negative HSI does not necessarily mean the presence of "mild cold stress".

Table 5

"1-Hr. Heat Tolerance" Using Prescriptive Zone *					Other Comparisons **			
Activity	T_{db} & T_g (°C)	T_{wb} (°C)	P_w partial (Torr)	RH*** (%)	HSI	WBGT (°C)	PHEL (hr:min)	CVR (%)
Sedentary	35.4	35.4	43.1	100	-32.1	35.4	5:10	56
(58.2 $W{\cdot}m^{-2}$)	42.2	34.8	37.9	61	137.9	37.0	4:00	52
	47.8	34.3	33.7	41	75.9	38.4	3:20	48
Light Work	34.3	34.3	40.5	100	-57.3	34.3	2:50	45
(116.3 $W{\cdot}m^{-2}$)	41.7	33.8	35.4	59	82.8	36.2	2:05	40
	46.9	33.3	31.4	40	62.3	37.4	1:40	37
Medium Work	34.1	34.1	40.1	100	-85.7	34.1	0:10	32
(174.5 $W{\cdot}m^{-2}$)	41.7	33.8	35.4	59	88.7	36.2	0:05	26
	47.2	33.4	31.5	39	66.5	37.6	0:05	22
"30-Min. Heat Tolerance" Using Prescriptive Zone *								
Medium Work	34.9	34.9	41.9	100	-55.8	34.9	0:10	30
(174.5 $W{\cdot}m^{-2}$)	42.2	34.8	37.9	61	157.9	37.0	0:05	24
	48.3	34.6	34.2	40	89.0	38.7	0:05	19

* Adapted from Nishi and Gagge.[41]

** Using STEP-M2 Abbreviated (See Appendix), with PHEL's rounded to the nearest 5 mins.

*** Relative humidity, as obtained from STEP-M2 Abbreviated.

Note: There are considerable differences within the literature as to definitions of physical activity relative to MR, therefore, the MR's given in this table are those appropriate to uses by Nishi and Gagge.[41] PHEL's of very short lengths of time are comparable with Bell et. al.[8] in the sense that the PHEL's would be "safe" for 99% of the population of unacclimatized, fit exposees.

Initial Field Surveys and Development of Analyses and Corrective Programs

A series of 15 special field surveys were conducted in industrial-type environments. The operational objectives of the surveys were to determine the range of thermal conditions to which workers were exposed, the magnitude of physiological strain during routine work in these environments, and to attempt to identify primary problem areas where corrective engineering actions could most significantly minimize high levels of heat stress. In order to permit comprehensive and more expeditious monitoring of the environment and physiological parameters a number of techniques, developed originally for laboratory research, were introduced into the field surveys. Critical data from the 15 initial surveys are summarized in Table 6.

Table 6

	Average Range	Maximum Range
Environmental Factors:		
Dry-bulb Temp. (°C)	46.7 - 55.0	65.6 - 73.9
Wet-bulb Temp. (°C)	29.4 - 33.9	40.6 - 73.9
Globe Temp. (°C)	63.3 - 67.2	68.3 - 82.2
Effective Air Movement Over Men (m/sec)	0.10 - 1.78	1.78 - 7.62
Mean Radiant Temp. (°C)	75.6 - 85.0	87.2 - 106.7
Partial Vapor Pressure In Air (Torr)	17.6 - 53.9	11.9 - 82.0
Relative Humidity (%)	14.9 - 68.9	6.2 - 100.0
Physiological Factors:		
Mean Skin Temp. of Men (°C)	38.8 - 41.6	41.9 - 45.4
Rectal Temp. (°C)	38.6 - 39.3	39.4 - 40.2
Heart Rates (beats·min^{-1})	147 - 176	180 - 190

As has been presented in this text, there are many combinations of environmental and physiological factors which can be used to obtain practical estimates of environmental stress and to predict the impact of heat stress upon and within man. Fortunately, the computer programs SPEEDARD-I and -II* have been in large scale usage[42] to integrate heat stress and strain data. These programs, designed for bulk data processing in a Univac 1108 at the National Bureau of Standards, were reviewed and markedly condensed to provide the most significant 20 outputs for these special field surveys. The resultant SHIP-6/4 program, requiring only 7 inputs, was modified for operation in a Hewlett-Packard HP-65 Programmable Pocket Calculator.[42] SHIP-6/4 was gradually improved as there were needs for more descriptive information as the surveys proceeded. The most important change, prior to designing the third generation program STEP**, was to develop the equations for estimating mean skin temperature (T_{sk}) and rectal temperature (T_{re}) from 213 sets of data (See Table A-1 of the Appendix); in turn, the estimated T_{sk} was used as a means of better correcting radiant (R) and convective (C) heat transfer, E_{req}, E_{max} and HSI. Furthermore, cardiovascular factors monitored in both laboratory and field studies, within the heat stress ranges noted in Table 6, were selected for their value in STEP programs. The techniques for monitoring the cardiovascular factors, steps to carry out the necessary calculations, and meaning of the products have been presented elsewhere.[15,22] The pertinent aspects relative to t_{wm} MR's from 50.0 - 146.5 W·m^{-2} and t_{wm} WBGT's from 19.8 - 49.7°C are presented in the Appendix (Tables A-2 - A-5 and STEP-M2). Therefore, in the

* Unique computer programs within the Heat Stress Division, NMRI.

** STEP is the master program used to develop STEP-M2 Abbreviated as given in the Appendix.

final development of the STEP series of programs, for the most advanced, programmable, self-contained, portable calculator*, the cardiovascular factors were incorporated with heat stress analysis equations such that one could easily obtain practical estimates of environmental heat stress and resultant physiological strain. To assist the many requests for the now obsolete SHIP-6/4 program written for the HP-65, and the increasing number of requests for STEP-M2 Abbreviated, the HP-97 program is given in the Appendix for STEP-M2 Abbreviated. STEP-E2 is the same as STEP-M2, but STEP-E2 is written for mixed English and metric inputs and outputs. Another advantage of the STEP programs is the section which permits calculation of maximum allowable exposures (MAE) for noise levels without hearing protection; as noise levels were monitored in all heat stress surveys, this portion of the STEP programs became very important.

Key to analysis of heat stress data from surveys is the quality of the heat stress data obtained from the industrial-type environments. Therefore, two series of evaluations were conducted to find a simple, light weight, fast response, small electronic device which measures and displays values for T_{db}, T_{wb}, T_g and air velocity within desired accuracies while exposed to dynamic heat stress conditions.[43,44] Over the range of temperatures to be encountered and the types of hard usage and shipping constraints, there were five such devices** evaluated in changing environmental situations, as viewed by the devices. In reality, there were fixed environments of different T_{db}, T_{wb}, T_g and air movements which the electronic monitoring devices were moved into and out of for 30 minutes or more. From the standpoint of T_{db} and T_{wb} sensors absorbing radiant heat, the Bendix units were the most influenced and the Reuter-Stokes units were the least influenced by the radiant heat. From the standpoint of fastest T_g response, the Reuter-Stokes devices were the most comparable (within less than three minutes) with the values obtained from a Vernon globe that had been in position for 30 minutes or more. The electronic device which best met the defined performance needs[45] was the Reuter-Stokes digital display unit that had been built as part of a six sensing head monitor system.

A composite of the environmental and physiological findings from the special heat stress surveys was assembled and subjected to critical review at various levels of policy, research and development, and operational supervision. This led to the formulation of a high temperature/heat stress correction program which was divided into seven major categories; maintenance, medical, design, development, education/training, emergency ventilation problems, and related topics. Each of the categories had a number of sub-elements to accomplish the objectives of the categories. The most decisive phase of the total program was to determine if a routine engineering overhaul was sufficient to minimize the heat stress and strain or if additional corrective engineering actions were required.

Three separate industrial-type settings were used to compare the impact of routine overhauls and the additional corrective engineering actions. Settings No. 1 and No. 2 were alike in terms of layout of machinery, types of machinery and operational status. Setting No. 3 was documented to be the highest heat stress industrial-type setting found during the special heat stress surveys. A general comparison of what was to be done is given in Table 7. The emphasis of the additional corrective engineering actions was to ensure that steam leaks were reduced as much as possible, that the majority of heat radiating surfaces were sufficiently insulated, and that there was a more effective delivery of ventilating air to work sites and improved exhaust of air from the areas. These actions were undertaken to produce a combined effect of increasing the economy and performance of both the workers and the equipment. Followup evaluations, after returning the Settings to full

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* Hewlett-Packard HP-97; for HP-67 operations delete SPC steps and it is recommended that R/S steps be substituted for PRTX steps.

** Light Laboratories Min-Lab 3 (England), with anemometer; Bendix WBGT Meter (manufactured 1972), finely adjusted prototype with anemometer; Bendix WBGT Meter (manufactured 1975), pre-production unit without anemometer; Reuter-Stokes RSS-211 Analog Readout, commercial grade without anemometer; and Reuter-Stokes RSS-211 Special Digital Readout unit [also known as the NMR&D MK-I/S(LED)], a linearized unit with anemometer.

operation, were scheduled at approximately six month intervals for no less than one year.

Table 7

Industrial Setting No.	Basic Approach
1	To receive a routine overhaul and completion of previously scheduled alterations.
2	To receive a routine overhaul, completion of the same previously scheduled alterations as Setting No. 1, and accomplishment of additional corrective engineering actions. (Setting No. 2 was used for the most direct comparison with Setting No. 1)
3	To receive a routine overhaul, completion of previously scheduled alterations, and accomplishment of additional corrective engineering actions. (Setting No. 3 was to serve as a means of evaluating the benefits of the additional engineering actions in what had been the highest heat stress setting found during the special heat stress surveys.)

Present Results of Engineering Actions to Minimize High Heat Stress

Comparative environmental and physiological data from followup evaluations for the corrective action program in industrial-*type* Settings No. 1 - No. 3 have revealed significant reductions of high heat stress and physiological strain through a comprehensive approach to the total problem, rather than pursuing routine overhauls in anticipation that the overhauls alone will significantly minimize heat stress. Table 8 clearly shows that it was possible to decrease the level of heat stress, even in the worst thermal stress situation reported here, to the point where routine maintenance could be conducted much more efficiently and a small reduction of heat stress continued over a one year time after restoring the Setting back into operation.

Table 8

Averaged Data from 14 Sites in Setting No. 3

Environmental Factors and PHEL's	Pre-Corrective Actions	Post-Corrective Actions 6 Months	12 Months
T_{db} (°C)	53.9	37.1	39.6
T_{wb} (°C)	33.5	26.8	27.0
T_g (°C)	71.5	43.9	41.2
Effective Air Velocity Over Workers (m/sec)	1.15	1.27	1.27
* T_r (°C)	102.5	53.9	43.3
P_w partial (Torr)	29.7	21.6	20.7
t_{wm} WBGT (°C)	43.2	31.3	31.2
PHEL's for t_{wm} MR's: (hrs:mins)			
88.4 $W \cdot m^{-2}$	1:20	7:10	7:10
146.5 $W \cdot m^{-2}$	0:20	2:10	2:10

* T_r = mean radiant temperature.

Summarized results of PHEL values, body temperatures and cardiovascular factors are presented in Table 9 for all three industrial-type settings. This information clearly indicates the value of a comprehensive approach to heat stress rather than expecting routine engineering overhauls alone to combat high heat stress.

Table 9

Averaged Data from Settings No. 1, No. 2 & No. 3

Setting No.	Corrective Action Phase	PHEL (hrs:mins) Normal t_{wm} MR	PHEL (hrs:mins) Maximum t_{wm} MR	T_{sk} (°C)	T_{re} (°C)	Cardiovascular Factors * HR	SP/DP	MAP	CVR
2	30 Days Post-Action	8:00+	6:00	34.6	37.8	98	138/77	95	83
	6 Mos. Post-Action	8:00+	6:00	34.8	37.5	98	137/76	95	84
	12 Mos. Post-Action	8:00+	3:40	35.0	37.6	98	134/74	93	87
1	8 Mos. Post-Action	3:20	1:00	37.5	39.0	128	207/51	75	15
3	Pre-Action	1:20	0:20	44.9	39.8	180	184/42	71	1
	6 Mos. Post-Action	7:10	2:10	36.4	38.1	107	165/75	93	63
	12 Mos. Post-Action	7:10	2:10	34.8	37.5	109	171/72	92	59

* The cardiovascular factors are defined and in the following units: HR = heart rate (beats·min^{-1}); SP = systolic blood pressure (mm Hg); DP = diastolic blood pressure (mm Hg); MAP = estimated mean arterial blood pressure (mm Hg); and, CVR = estimated cardiovascular reserve (%).

The cardiovascular responses in Setting No. 1 were such during the first one-third of the trials that compensation was approaching its maximum; thereafter, there was rapid decompensation due to the excessively high level of heat stress at the same time that workers were attempting to perform their normal tasks. As discussed earlier, the low HR's were not descriptive of heat tolerance limits being reached as the strain was shifted to other aspects of the cardiovascular system.

Summary

Major accomplishments have been achieved during the past few years in the control of industrial heat stress. It is highly encouraging to note that through the strong support of management[46] and the capability of biomedical R&D to assist both management and industrial-type workers that significant reductions of excessive heat stress are a reality today. The utilization of research technology has permitted the establishment of an objective basis to dramatically improve highly limiting heat stress situations which have had a profound, adverse impact upon man and industry.

Documentation of the ranges of industrial heat stress and the physiological responses to that stress was the first step in initiating a direct attack upon high levels of heat stress. Once evidence could be produced to show the problems involved, a series of phases were formulated whereby the goals of reduced levels of heat stress, increased work function and availability of objective exposure limits were instituted to guide the design of better working environments. The establishment of comprehensive physiological heat exposure criteria was imperative in order to

develop true exposure limits. As exposure limits are a function of the intensity of the exposure, length of time in the specific environment and the rate of performing work under those conditions, it was possible to develop the PHEL concept and exposure limit curves which recognized that physiological strain would be present but also would be reversible. Meanwhile, a series of computer programs were prepared to integrate the variables of heat stress and strain. This was done in such a manner as to permit practical partitioning of the components of the stress, serve as a guide in making recommendations that would produce significant changes of the environment, and better predict alterations of limiting physiological systems.

The benefits of the program to date have been illustrated in terms of a marked reduction of physiological strain and nearly a sixfold increase of maximum exposure times for greater productivity. In areas where corrective engineering actions from the program are not yet existent or are not completed, the PHEL concept and associated guidelines[37] have not resulted in a detectable increase of morbidity. However, it is very likely that none of the operational exposure limiting methods today can be safe for all workers, even though there is reasonable assurance that the PHEL concept is safe in a practical sense up to the limits for greater than 95 percent of the fit population of workers within the range of 19 - 43 years of age. Therefore, in support of Dinman et. al.,[47] a standard for heat stress must neither be overly conservative on the side of the workers nor too liberal on the side of management. The most practical approach to an industrial-type standard for heat tolerance limits is where workers perform within their limits as shown herein, while at the same time a concerted effort is made to minimize the intensity of the environmental stresses.

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Appendix

Table A-1 Summary of T_r Encountered versus T_{sk} Determined and T_{re} Measured *

T_r Range (°C)	N	T_r Encountered (°C)	T_{sk} Determined (°C)	T_{re} Measured (°C)
32.2 - 37.7	24	33.9 ± 0.37	33.4 ± 0.13	36.6 ± 0.31
37.8 - 43.3	44	40.9 ± 0.18	34.5 ± 0.14	37.5 ± 0.04
43.3 - 48.8	16	45.7 ± 0.42	35.1 ± 0.24	37.7 ± 0.04
48.9 - 54.4	22	51.3 ± 0.28	35.8 ± 0.13	38.0 ± 0.07
54.5 - 59.9	20	57.3 ± 0.30	36.6 ± 0.18	38.1 ± 0.09
60.0 - 65.5	15	63.3 + 0.41	38.3 ± 0.36	38.4 ± 0.03
65.6 - 71.1	22	68.0 ± 0.33	39.3 ± 0.31	38.6 ± 0.03
71.2 - 76.6	12	74.1 ± 0.47	39.7 ± 0.08	38.8 ± 0.02
76.7 - 82.2	12	79.5 ± 0.52	40.6 ± 0.09	39.1 ± 0.03
82.3 - 87.7	15	84.4 ± 0.43	41.4 ± 0.07	39.2 ± 0.02
87.8 - 93.3	11	90.4 ± 0.51	42.5 ± 0.08	39.5 ± 0.02

* Subjects age range 19 - 43 years. Subjects normally clothed. T_r range 32.2 - 93.3 °C. t_{wm} MR range 50.0 - 146.5 $W \cdot m^{-2}$. All values given in above Table are expressed as Mean ± Standard Error when appropriate. Total N = 213.

Best fit estimates of T_{sk} and T_{re}:

Estimated T_{sk} (°C)

$$T_{sk} = 28.857\ e^{4.321 \cdot 10^{-3}\ T_r}$$

N = 213
r = 0.953
t = 45.4796
p < 0.0001

Estimated T_{re} (°C)

$$T_{re} = 27.366 + (2.678 \ln T_r)$$

N = 213
r = 0.944
t = 41.5976
p < 0.0001

T_r = mean radiant temperature. T_{sk} = mean skin temperature. T_{re} = rectal temperature. t_{wm} MR = time-weighted-mean metabolic rate.

Appendix

Table A-2 Summary of Cardiovascular Factors versus t_{wm} WBGT at t_{wm} MR 50.0 $W \cdot m^{-2}$

Factors	t_{wm} WBGT (range 19.8 - 22.2°C)				
	20.8 ± 0.1 (n = 27)	21.4 ± 0.2 (n = 16)	20.7 ± 0.2 (n = 22)	18.9 ± 0.1 (n = 19)	20.6 ± 0.1 (n = 15)
HR	81.7 ± 1.5	94.0 ± 2.4	90.6 ± 1.6	83.7 ± 2.6	76.0 ± 3.5
SP	130.8 ± 1.2	130.9 ± 1.9	130.3 ± 1.1	128.3 ± 0.8	124.9 ± 2.5
DP	78.5 ± 1.4	80.7 ± 1.4	83.1 ± 1.1	84.5 ± 0.7	72.5 ± 2.0
MAP	95.9 ± 1.2	97.4 ± 1.4	98.6 ± 0.9	99.1 ± 0.5	89.8 ± 2.1
CO *	4.9 ± 0.1	5.2 ± 0.2	4.9 ± 0.1	4.4 ± 0.1	5.1 ± 0.1
TVR	1572.7 ± 48.9	1526.7 ± 57.0	1641.9 ± 42.2	1801.9 ± 50.9	1430.2 ± 57.2
CVR	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0

Table A-3 Summary of Cardiovascular Factors versus t_{wm} WBGT at t_{wm} MR 88.4 $W \cdot m^{-2}$

Factors	t_{wm} WBGT (range 23.8 - 39.5°C)				
	26.4 ± 0.5 (n = 22)	30.5 ± 1.1 (n = 5)	32.7 ± 1.4 (n = 5)	35.4 ± 1.0 (n = 8)	37.8 ± 0.0 (n = 4)
HR	86.0 ± 3.1	106.0 ± 1.9	119.0 ± 4.1	105.6 ± 1.6	152.5 ± 3.2
SP	122.8 ± 1.4	138.0 ± 4.0	119.0 ± 4.0	121.9 ± 3.2	103.8 ± 1.3
DP	73.3 ± 1.8	82.8 ± 2.3	82.4 ± 2.4	63.4 ± 5.0	34.8 ± 3.5
MAP	89.7 ± 1.5	101.2 ± 2.6	94.6 ± 2.9	82.7 ± 4.0	57.8 ± 2.6
CO *	5.6 ± 0.2	6.4 ± 0.5	6.3 ± 0.3	8.3 ± 0.5	15.7 ± 0.8
TVR	1288.4 ± 35.6	1277.9 ± 56.9	1216.3 ± 89.9	829.5 ± 83.1	298.6 ± 0.8
CVR	88.1 ± 3.5	91.1 ± 4.9	69.2 ± 3.2	32.8 ± 5.8	9.6 ± 3.6

Values given as Mean ± Standard Error. t_{wm} = time-weighted-mean. HR = heart rate ($beats \cdot min^{-1}$). SP = systolic blood pressure (mm Hg). DP = diastolic blood pressure (mm Hg). MAP = mean arterial pressure (mm Hg). CO * = estimated cardiac output ($liters \cdot min^{-1}$); these values are conservative estimates. TVR = estimated total vascular resistance ($dynes \cdot sec \cdot cm^{-5}$). CVR = estimated cardiovascular reserve (%).

Appendix

Table A-4 Summary of Cardiovascular Factors versus t_{wm} WBGT at 111.7 $W \cdot m^{-2}$

Factors	t_{wm} WBGT (range 20.7 - 49.7°C)				
	24.1 ± 0.5 (n = 22)	29.3 ± 1.5 (n = 5)	31.3 ± 0.0 (n = 4)	30.7 ± 0.6 (n = 11)	44.9 ± 1.4 (n = 12)
HR	8[illegible].5 ± 1.8	112.4 ± 2.7	91.5 ± 0.3	99.8 ± 2.5	145.3 ± 9.7
SP	126.[illegible] ± 1.3	146.2 ± 1.9	117.5 ± 0.9	119.2 ± 3.8	143.4 ± 8.5
DP	72.7 ± 1.4	78.4 ± 2.7	69.0 ± 0.6	59.6 ± 4.0	51.3 ± 3.2
MAP	90.4 ± 1.1	101.0 ± 1.8	85.0 ± 0.8	79.3 ± 3.9	82.0 ± 4.0
CO *	6.1 ± 0.2	7.2 ± 0.5	6.5 ± 0.1	7.6 ± 0.3	14.4 ± 1.4
TVR	1208.7 ± 44.9	1142.4 ± 107.6	1047.5 ± 16.4	867.7 ± 76.6	505.1 ± 55.3
CVR	83.2 ± 3.3	64.1 ± 13.8	63.7 ± 1.4	35.5 ± 5.4	15.3 ± 5.0

Table A-5 Summary of Cardiovascular Factors versus t_{wm} WBGT at 146.5 $W \cdot m^{-2}$

Factors	t_{wm} WBGT (range 21.7 - 37.3°C)				
	25.2 ± 0.4 (n = 31)	29.5 ± 0.6 (n = 19)	31.6 ± 1.0 (n = 12)	34.1 ± 0.8 (n = 12)	36.4 ± 0.0 (n = 6)
HR	90.9 ± 0.9	115.1 ± 3.3	122.6 ± 6.4	110.1 ± 1.9	131.8 ± 3.2
SP	131.7 ± 1.5	147.7 ± 3.0	136.3 ± 3.5	129.6 ± 3.5	116.8 ± 3.0
DP	79.1 ± 0.7	67.0 ± 1.7	70.3 ± 3.9	64.1 ± 3.8	27.5 ± 1.1
MAP	96.3 ± 0.7	93.9 ± 1.7	92.2 ± 1.9	85.9 ± 3.4	57.3 ± 0.4
CO *	5.1 ± 0.1	9.6 ± 0.4	8.1 ± 0.7	7.8 ± 0.4	14.7 ± 0.3
TVR	1534.4 ± 28.7	807.9 ± 38.5	971.4 ± 71.8	923.0 ± 89.5	313.5 ± 8.5
CVR	78.1 ± 2.1	43.9 ± 3.4	43.4 ± 5.5	38.6 ± 6.0	1.1 ± 0.8

Values given as Mean ± Standard Error. t_{wm} = time-weighted-mean. HR = heart rate ($beats \cdot min^{-1}$). SP = systolic blood pressure (mm Hg). DP = diastolic blood pressure (mm Hg). MAP = mean arterial pressure (mm Hg). CO * = estimated cardiac output ($liters \cdot min^{-1}$); these values are conservative estimates. TVE = estimated total vascular resistance ($dynes \cdot sec \cdot cm^{-5}$). CVR = estimated cardiovascular reserve (%).

Thermal Analysis Metric Equations For Stress/Strain Evaluation Program (STEP-M2) Abbreviated

Appendix

Saturated Vapor Pressures:

$P_{s,T}$ = [Antilog (2.339 - X·Y)]·P

where: $P_{s,T}$ = saturated vapor pressure at T_{db} or T_{wb} = (Torr)

$$X = \frac{[A^3(1.17\cdot10^{-8})] + [A\ (5.868\cdot10^{-3}) + 3.244]}{1 + [A\ (2.188\cdot10^{-3})]}$$

$$A = 647.27 - [(T_{db} \text{ or } T_{wb}) + 273.15]$$

$$Y = \frac{A}{(T_{db} \text{ or } T_{wb}) + 273.15}$$

T_{db} = dry-bulb temperature (°C)

T_{wb} = wet-bulb temperature (aspirated) (°C)

P = barometric pressure (Torr)

Solve using T_{db} for $P_{s,T_{db}}$; and, T_{wb} for $P_{s,T_{wb}}$

Partial Vapor Pressure:

$$P_w \text{ partial} = P_{s,T_{wb}} - [[(6.6\cdot10^{-4}\ P)(T_{db} - T_{wb})] \cdot [1 + (T_{db} - T_{wb})\ 1.5\ 10^{-3}]]$$

where: P_w partial = (Torr)

Relative Humidity:

$$RH = (P_w \text{ partial} / P_{s,T_{db}}) \cdot 100 = (\%)$$

Mean Radiant Temperature:

$$T_r = [(T_g + 273.15)^4 + [(0.247\cdot10^9\ V^{0.5})(T_g - T_{db})]]^{0.25} - 273.15$$

where: T_r = mean radiant temperature (°C)

T_g = globe temperature (°C)

V = air velocity (m/sec)

Terms, where appropriate, are consistent with the International Union of Physiological Sciences. (Glossary of Terms for Thermal Physiology, JAP 6(35);941-961, 1973)

Once a symbol is defined herein the repeat of the symbol is not redefined.

Appendix

Estimated Skin Temperature:

$$T_{sk} = 28.857\ e^{4.321 \cdot 10^{-3}\ T_r} = (^\circ C)$$

where: Estimated T_{sk} is applicable to normally clothed man within the ranges of T_r 32.2 - 93.3 °C and time-weighted-mean metabolic rate 50.0 - 146.54 $W \cdot m^{-2}$. ($N = 213$, $r = 0.953$, $t = 45.4796$, $p<0.0001$)

Estimated Rectal Temperature:

$$T_{re} = 27.37 + (2.68\ \mathrm{Ln}\ T_r) = (^\circ C)$$

where: Estimated T_{re} is applicable to normally clothed man within the ranges of T_r 32.2 - 93.3 °C and time-weighted-mean metabolic rate 50.0 - 146.54 $W \cdot m^{-2}$. ($N = 213$, $r = 0.944$, $t = 41.5976$, $p<0.0001$)

Radiant Heat Exchange:

$$R = \frac{[13.130\ (T_r - T_{sk})]}{m^2}\ 0.7 = W \cdot m^{-2} \quad \text{(reduced 30\% due to clothing)}$$

where: m^2 = DuBois surface area from $[71.84 \cdot 10^{-4}\ Ht^{0.725} \cdot W^{0.425}]$, where Height in cm. and Weight in kg.

Convective Heat Exchange:

$$C = \frac{[13.456\ V^{0.58}\ (T_{db} - T_{sk})]}{m^2}\ 0.7 = W \cdot m^{-2} \quad \text{(reduced 30\% due to clothing)}$$

Evaporation Required For Heat Balance:

$$E_{req} = t_{wm}\ MR + R + C = W \cdot m^{-2} \quad \text{(using R and C as reduced above)}$$

where: t_{wm} = time-weighted-mean

As in the case of t_{wm} Metabolic Rate the following applies

$$t_{wm}\ MR = \frac{[(t_1 \cdot MR_1) + (t_2 \cdot MR_2) + \ldots. + (t_n \cdot MR_n)]}{t_1 + t_2 + \ldots. + t_n}$$

where: t_1 is the first time interval and MR_1 is the metabolic rate for the respective time interval, etc.

Appendix

Maximum Evaporative Capacity:

$$E_{max} = \frac{[25.15\ V^{0.58}\ [[(T_{sk} - 34.94)\ 2.34] + 42.00] - P_w \text{ partial}]}{m^2}\ 0.7$$

where: $E_{max} = W \cdot m^{-2}$ (reduced 30% due to clothing)

Heat Stress Index (Belding and Hatch):

$HSI = [(E_{req}/E_{max}) \cdot 100]$ (unitless)

Wet-Bulb Globe Temperature Index: (See Text)

$WBGT = [(0.1\ T_{tb}) + (0.7\ T_{wb}) + (0.2\ T_g)] = (°C)$

Physiological Heat Exposure Limits (Dasler): (See Text)

PHEL I ("A") for t_{wm} MR 88.39 $W \cdot m^{-2}$

$PHEL\ I = 741.594 \cdot 10^6\ WBGT^{-5.369}$

where: PHEL in hrs. with mins. in decimal; PHEL converted to hrs:min in STEP-M2 Abbreviated.

Laboratory data: $N = 147$, $r = -0.997$, $t = 155.1063$, $p < 0.0001$
Field data: $N = 66$, $r = -0.995$, $t = 79.6997$, $p < 0.0001$

PHEL II for t_{wm} MR 100.02 $W \cdot m^{-2}$

$PHEL\ II = 592.561 \cdot 10^6\ WBGT^{-5.356}$

where: PHEL in hrs. with mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated.

Laboratory data: $N = 132$, $r = -0.998$, $t = 180.0070$, $p < 0.0001$
Field data: $N = 52$, $r = -0.994$, $t = 64.2589$, $p < 0.0001$

PHEL III ("B") for t_{wm} MR 111.65 $W \cdot m^{-2}$

$PHEL\ III = 487.461 \cdot 10^5\ WBGT^{-5.351}$

where: PHEL in hrs. and mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated.

Laboratory data: $N = 137$, $r = -0.997$, $t = 149.6623$, $p < 0.0001$
Field data: $N = 57$, $r = -0.992$, $t = 58.2778$, $p < 0.0001$

PHEL IV for t_{wm} MR 123.28 $W \cdot m^{-2}$

$PHEL\ IV = 432.399 \cdot 10^6\ WBGT^{-5.371}$

where: PHEL in hrs. and mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated.

Laboratory data: $N = 128$, $r = -0.997$, $t = 144.5875$, $p < 0.0001$
Field data: $N = 48$, $r = -0.993$, $t = 57.0198$, $p < 0.0001$

Appendix

PHEL V for t_{wm} MR 134.91 $W \cdot m^{-2}$

$$PHEL\ V = 334.370 \cdot 10^6\ WBGT^{-5.373}$$

where: PHEL in hrs. and mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated.

Laboratory data: $N = 67$, $r = -0.987$, $t = 49.3516$, $p < 0.0001$
Field data: $N = 20$, $r = -0.978$, $t = 19.8907$, $p < 0.0001$

PHEL VI ("C") for t_{wm} 146.54 $W \cdot m^{-2}$

$$PHEL\ VI = 207.825 \cdot 10^6\ WBGT^{-5.344}$$

where: PHEL in hrs. and mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated.

Laboratory data: $N = 46$, $r = -0.989$, $t = 44.3516$, $p < 0.0001$
Field data: $N = 12$, $r = -0.975$, $t = 13.8756$, $p < 0.0001$

$PHEL_{specific}$ for t_{wm} MR range 88.39 - 146.54 $W \cdot m^{-2}$

$$PHEL_{spec.} = [17.251 \cdot 10^8 - (12.967 \cdot 10^6\ t_{wm}\ MR) + (18.611 \cdot 10^3\ t_{wm}\ MR^2)]\ WBGT^{-5.360}$$

where: $PHEL_{specific}$ in hrs. and mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated. $PHEL_{specific}$ applies to WBGT's through 55 °C. The first three coefficients of $PHEL_{specific}$ were derived from PHEL's I - VI above; $N = 6$, $r = 0.994$, $t = 18.4887$, $p < 0.0001$. Exponent for WBGT based upon $N = 6$ with SE ±0.005.

Estimated Recovery Times:

Minimum Recovery Time = $PHEL_{spec.} \cdot 1.195$

where: $PHEL_{specific}$ prior to conversion to hrs:mins. Minimum recovery time based upon a minimum Relaxation Allowance of 119.5% (See Footnote). STEP-M2 converts to hrs:mins.

General Recovery Time = $PHEL_{spec.} \cdot 1.994$

where: $PHEL_{specific}$ prior to conversion to hrs:mins. General recovery time based upon a general Relaxation Allowance of 199.4% (See Footnote). STEP-M2 converts to hrs:mins.

Maximum Recovery Time = $PHEL_{spec.} \cdot 2.260$

where: $PHEL_{specific}$ prior to conversion to hrs:mins. Maximum recovery time based upon a maximum Relaxation Allowance of 226.0% (See Footnote). STEP-M2 converts to hrs:mins.

Relaxation Allowance concept from: Curie, R. M. Work Study. Coppclark Pub., Co.; Toronto, Canada. (Chapter 12, pp. 156 - 164) Reprinted 1969.

Appendix

Cardiovascular Factors Without Subjectively Detectable Levels Of Fuel Combustion Gases or Pre-Combustion Fuel Vapors:

Heart Rate (beats·min^{-1})

$$HR = [48.15 + (0.08\ t_{wm}\ MR) + (1.64\ WBGT)]$$

$N = 277$	$r_{x \cdot yz} = 0.4052$	$t = 7.3497$	$p < 0.0001$
	$r_{y \cdot xz} = 0.6518$	$t = 14.2531$	$p < 0.0001$
	$r_{z \cdot xy} = 0.6519$	$t = 14.2544$	$p < 0.0001$

Systolic Blood Pressure (mm Hg)

$$SP = [125.67 + (0.06\ t_{wm}\ MR) - (0.08\ WBGT)]$$

$N = 277$	$r_{x \cdot yz} = 0.5741$	$t = 11.6279$	$p < 0.0001$
	$r_{y \cdot xz} = 0.5627$	$t = 11.2876$	$p < 0.0001$
	$r_{z \cdot xy} = 0.1526$	$t = 2.5610$	$p < 0.012$

Diastolic Blood Pressure (mm Hg)

$$DP = [107.88 - (0.01\ t_{wm}\ MR) - (1.29\ WBGT)]$$

$N = 277$	$r_{x \cdot yz} = 0.5215$	$t = 10.1349$	$p < 0.0001$
	$r_{y \cdot xz} = 0.7196$	$t = 17.1839$	$p < 0.0001$
	$r_{z \cdot xy} = 0.6506$	$t = 14.2607$	$p < 0.0001$

Mean Arterial Pressure (mm Hg)

$$MAP = [109.669 + (0.022\ t_{wm}\ MR) - (0.765\ WBGT)]$$

$N = 277$	$r_{x \cdot yz} = 0.4862$	$t = 9.2265$	$p < 0.0001$
	$r_{y \cdot xz} = 0.6079$	$t = 12.6957$	$p < 0.0001$
	$r_{z \cdot xy} = 0.4445$	$t = 8.2293$	$p < 0.0001$

Subscripts of multiple correlation coefficients (r's) apply as follows: $x = t_{wm}$ MR, y = WBGT, and z = cardiovascular factor.

Breakdown of sets of observations as follows: t_{wm} MR 50.01 W·m^{-2} (N = 99), t_{wm} MR 88.39 W·m^{-2} (N = 45), t_{wm} MR 111.65 W·m^{-2} (N = 52), and t_{wm} MR 146.54 W·m^{-2} (N = 81); WBGT's obtained as t_{wm} during the determine t_{wm} MR's. Total N = 277 per cardiovascular factor, t_{wm} MR and WBGT.

Appendix

Estimated Cardiac Output (liters·min^{-1}) (See Text regarding evidence of conservative estimates by the technique utilized)

$$CO = [-2.608 - (0.001\ t_{wm}\ MR) - (0.765\ WBGT)]$$

N = 277	$r_{x \cdot yz} = 0.5345$	t = 10.[illegible]876	$p < 0.0001$
	$r_{y \cdot xz} = 0.8186$	t = 23.6327	$p < 0.0001$
	$r_{z \cdot xy} = 0.7842$	t = 20.9612	$p < 0.0001$

Estimated Cardiovascular Reserve (%) (See Text)

$$CVR = [170.978 - (0.242\ t_{wm}\ MR) - (2.843\ WBGT)]$$

N = 277	$r_{x \cdot yz} = 0.6229$	t = 13.2033	$p < 0.0001$
	$r_{y \cdot xz} = 0.7879$	t = 21.2174	$p < 0.0001$
	$r_{z \cdot xy} = 0.8305$	t = 24.7231	$p < 0.0001$

Supplementary Section Of STEP-M2 Abbreviated:

Maximum Allowable Exposure Time Without Hearing Protection * Based Upon Noise Level

$$MAE_{noise} = [\text{AntiLn}\,[(\text{db A} - 105.00)/-7.21]]$$

where: db A = noise level on "slow" A scale

Note: The above equation is a transposition of a logarithmic curve fit with r = 1.0000; the equation may also be written as an exponential curve fit (with r = 1.0000) in the following form:

$$MAE_{noise} = 2097151.954\ e^{-0.138629\ \text{db A}}$$

* From data provided in: Control of Noise (12), American Foundrymen's Society, 3rd Ed., 1972.

Bureau of Medicine and Surgery, Navy Department, BUMED Instruction 6260.6B, 5 March 1970.

Data from these sources were subjected to the least squares family of regression curves to provide the above equations.

Appendix

STEP-M2 Abbreviated Program For Hewlett-Packard Calculator (HP-97)*

(Total running time, including inputs and all prints, averages 1 min. 56 sec.)

Inputs:

T_{db} (LBL A); T_{wb} (LBL B or R/S); T_g (LBL C or R/S); V (LBL D or R/S); t_{wm} MR (LBL E or R/S). [T_{db} must be entered using key "A"; T_{wb}, T_g, V and t_{wm} MR may be entered by using the designated key or by use of R/S key. Using the user defined key permits altering the sequence of entries; however, STEP-M2 starts running immediately after entering t_{wm} MR.]

Grouped Order of Printing: (each group separated by a space)

[T_{db}; T_{wb}; T_g; V; t_{wm} MR] [$P_{s,T_{db}}$; $P_{s,T_{wb}}$; P_w partial] [RH] [T_r] [R; C; E_{req}; E_{max}] [WBGT] [$PHEL_{specific}$] [Minimum Recovery Time; General Recovery Time; Maximum Recovery Time] [PHEL I; PHEL II; PHEL III; PHEL IV; PHEL V; PHEL VI] [HSI] [T_{sk}; T_{re}] [HR; SP; DP; MAP; CO; CVR] [T_{db}; T_{wb}; T_g; V; t_{wm} MR are repeated at the end as a means of rechecking and/or permitting comparisons]

Supplementary Portion of STEP-M2 for MAE_{noise}:

Two options exist for calculating MAE_{noise}: (1) After STEP-M2 has run as given above, input db A using key "A" and MAE_{noise} will be printed in hrs:mins provided the program from Card #4 is still in the HP-97; or, (2) Insert Card #4 (both sides) and input db A using key "A" to get MAE_{noise} printed.

Card #1

001	*LBLA	017	SPC	033	3	049	STO3	065	7	081	STO8
002	DSP2	018	.	034	.	050	RCLB	066	EEX	082	X
003	STOA	019	5	035	1	051	RCLI	067	CHS	083	+
004	PRTX	020	8	036	5	052	+	068	8	084	3
005	R/S	021	y^x	037	STOI	053	STO4	069	STO7	085	.
006	*LBLB	022	STO0	038	+	054	RCL6	070	X	086	2
007	STOB	023	RCLD	039	STO2	055	X≠Y	071	RCL3	087	4
008	PRTX	024	R/S	040	6	056	-	072	5	088	3
009	R/S	025	*LBLE	041	4	057	STO5	073	.	089	8
010	*LBLC	026	STOE	042	7	058	RCL3	074	8	090	STO9
011	STOC	027	PRTX	043	.	059	ENT↑	075	6	091	+
012	PRTX	028	SPC	044	2	060	X^2	076	8	092	RCL3
013	R/S	029	SPC	045	7	061	X	077	3	093	2
014	*LBLD	030	RCLA	046	STO6	062	1	078	EEX	094	.
015	STOD	031	2	047	X⇄Y	063	.	079	CHS	095	1
016	PRTX	032	7	048	-	064	1	080	3	096	8

* (from title) STEP-M2 Abbreviated provides 68% of the full STEP-2 Program. The program as given herein permits autoloading of Sides #1 of Cards #2 - #4; when Sides #2 of Cards #2 - #4 are entered the program restarts automatically, should and ERROR display occur reenter Sides #1 and #2 of that Card and press key R/S to continue program. All factors printed in units of time are printed as hrs.mins, the decimal point serves as a colon (:); e.g., 3.55 in units of time is 3:55 as hrs:mins.

Appendix

Card #1, continued

097	7	156	2	215	RCLI
098	8	157	.	216	+
099	EEX	158	3	217	ENT↑
100	CHS	159	3	218	ENT↑
101	3	160	8	219	ENT↑
102	X	161	8	220	X
103	1	162	X⇄Y	221	X
104	+	163	-	222	X
105	÷	164	10^x	223	PSE
106	RCL3	165	7	224	RTN
107	RCL2	166	6		
108	÷	167	0		
109	X	168	X		
110	2	169	STO4		
111	.	170	PRTX		
112	3	171	6		
113	3	172	.		
114	8	173	6		
115	8	174	EEX		
116	X⇄Y	175	CHS		
117	-	176	4		
118	10^x	177	STO7		
119	7	178	RCLA		
120	6	179	RCLB		
121	0	180	-		
122	X	181	STO1		
123	STO2	182	RCL7		
124	DSP1	183	7		
125	PRTX	184	6		
126	RCL5	185	0		
127	ENT↑	186	X		
128	x^2	187	X		
129	X	188	RCL1		
130	RCL7	189	1		
131	X	190	.		
132	RCL5	191	1		
133	RCL8	192	5		
134	X	193	EEX		
135	+	194	CHS		
136	RCL9	195	3		
137	+	196	X		
138	RCL5	197	1		
139	2	198	+		
140	.	199	X		
141	1	200	RCL4		
142	8	201	X⇄Y		
143	7	202	-		
144	8	203	PRTX		
145	EEX	204	STO6		
146	CHS	205	SPC		
147	3	206	RCL2		
148	X	207	÷		
149	1	208	EEX		
150	+	209	2		
151	÷	210	X		
152	RCL5	211	DSPØ		
153	RCL4	212	PRTX		
154	÷	213	SPC		
155	X	214	RCLC		

Card #2

001	RCLC
002	RCLA
003	-
004	RCLD
005	$\sqrt{x}$
006	.
007	2
008	4
009	7
010	EEX
011	9
012	X
013	X
014	+
015	$\sqrt{x}$
016	$\sqrt{x}$
017	RCLI
018	-
019	STO1
020	DSP1
021	PRTX
022	SPC
023	4
024	.
025	3
026	2
027	1
028	EEX
029	CHS
030	3
031	X
032	e^x
033	2
034	8
035	.
036	8
037	5
038	7
039	X
040	STO2
041	RCL1
042	LN
043	2
044	.
045	6
046	8
047	X

Card #2, continued

048	2	107	4	166	5
049	7	108	-	167	1
050	.	109	2	168	EEX
051	3	110	.	169	8
052	7	111	3	170	RCLE
053	+	112	4	171	1
054	STO3	113	X	172	2
055	RCL1	114	4	173	.
056	RCL2	115	2	174	9
057	-	116	.	175	6
058	1	117	0	176	.7
059	3	118	0	177	EEX
060	.	119	+	178	6
061	1	120	RCL6	179	X
062	3	121	-	180	-
063	0	122	RCLØ	181	RCLE
064	X	123	X	182	x^2
065	.	124	2	183	1
066	7	125	5	184	8
067	X	126	.	185	.
068	1	127	1	186	6
069	.	128	5	187	1
070	8	129	X	188	1
071	5	130	.	189	EEX
072	STOI	131	7	190	3
073	÷	132	X	191	X
074	STO4	133	RCLI	192	+
075	PRTX	134	÷	193	RCL9
076	RCLA	135	STO8	194	5
077	RCL2	136	PRTX	195	.
078	-	137	SPC	196	3
079	RCLØ	138	RCL7	197	6
080	X	139	X⇄Y	198	0
081	1	140	÷	199	CHS
082	3	141	EEX	200	y^x
083	.	142	2	201	X
084	4	143	X	202	STO5
085	5	144	STO4	203	→HMS
086	6	145	RCLA	204	DSP2
087	X	146	.	205	PRTX
088	.	147	1	206	SPC
089	7	148	X	207	RCL5
090	X	149	RCLB	208	1
091	RCLI	150	.	209	1
092	÷	151	7	210	9
093	STO5	152	X	211	.
094	PRTX	153	+	212	5
095	RCLE	154	RCLC	213	%
096	RCL4	155	.	214	→HMS
097	RCL5	156	2	215	PRTX
098	+	157	X	216	RCL5
099	+	158	+	217	1
100	STO7	159	STO9	218	9
101	PRTX	160	PRTX	219	9
102	RCL2	161	SPC	220	.
103	3	162	1	221	4
104	4	163	7	222	PSE
105	.	164	.	223	RTN
106	9	165	2	224	R/S

Card #3

001	%
002	→HMS
003	PRTX
004	RCL5
005	2
006	2
007	6
008	.
009	0
010	%
011	→HMS
012	PRTX
013	SPC
014	RCL9
015	5
016	.
017	3
018	6
019	9
020	CHS
021	y^x
022	7
023	4
024	1
025	.
026	5
027	9
028	4
029	EEX
030	6
031	X
032	→HMS
033	PRTX
034	RCL9
035	5
036	.
037	3
038	5
039	6
040	CHS
041	y^x
042	5
043	9
044	2
045	.
046	5
047	6
048	7
049	EEX
050	6
051	X
052	→HMS
053	PRTX
054	RCL9
055	5
056	.
057	3
058	5
059	1
060	CHS
061	y^x
062	4
063	8
064	7
065	.
066	4
067	6
068	1
069	EEX
070	6
071	X
072	→HMS
073	PRTX
074	RCL9
075	5
076	.
077	3
078	7
079	1
080	CHS
081	y^x
082	4
083	3
084	2
085	.
086	3
087	3
088	9
089	EEX
090	6
091	X
092	→HMS
093	PRTX
094	RCL9
095	5
096	.
097	3
098	7
099	3
100	CHS
101	y^x
102	3
103	3
104	4
105	.
106	3
107	7
108	0
109	EEX
110	6
111	X
112	→HMS
113	PRTX
114	RCL9
115	5
116	.
117	3
118	4
119	4
120	CHS
121	y^x
122	2
123	0
124	7
125	.
126	8
127	2
128	5
129	EEX
130	6
131	X
132	→HMS
133	PRTX
134	SPC
135	DSP1
136	RCL4
137	PRTX
138	SPC
139	RCL2
140	PRTX
141	RCL3
142	PRTX
143	SPC
144	4
145	8
146	.
147	1
148	5
149	RCLE
150	.
151	0
152	8
153	X
154	+
155	RCL9
156	1
157	.
158	6
159	4
160	X
161	+
162	DSPØ
163	PRTX
164	1
165	2
166	5
167	.
168	6
169	7
170	RCLE
171	.
172	0
173	6
174	X
175	+
176	RCL9
177	.
178	0
179	8
180	X
181	-
182	PRTX
183	1
184	0
185	7
186	.
187	8
188	8
189	RCLE
190	.
191	0
192	1
193	X
194	-
195	RCL9
196	1
197	.
198	2
199	9
200	X
201	-
202	PRTX
203	1
204	0
205	9
206	.
207	6
208	6
209	9
210	RCLE
211	.
212	0
213	2
214	2
215	X
216	+
217	RCL9
218	PSE
219	RTN
220	R/S

Card #4

001	.
002	7
003	6
004	5
005	X
006	-
007	DSP1
008	PRTX
009	2
010	.
011	6
012	0
013	8
014	CHS
015	RCLE
016	.
017	0
018	0
019	1
020	X
021	-
022	RCL9
023	.
024	3
025	5
026	6
027	X
028	+
029	PRTX
030	1
031	7
032	0
033	.
034	9
035	7
036	8
037	RCLE
038	.
039	2
040	4
041	2
042	X
043	-
044	RCL9
045	2
046	.
047	8
048	4
049	3
050	X
051	-
052	DSPØ
053	PRTX
054	SPC
055	SPC
056	SPC
057	SPC
058	RCLA
059	DSP2
060	PRTX
061	RCLB
062	PRTX
063	RCLC
064	PRTX
065	RCLD
066	PRTX
067	RCLE
068	PRTX
069	SPC
070	SPC
071	SPC
072	SPC
073	SPC
074	RTN
075	*LBLA
076	DSP1
077	PRTX
078	SPC
079	1
080	0
081	5
082	.
083	0
084	0
085	-
086	7
087	.
088	2
089	1
090	CHS
091	+
092	e^x
093	DSP2
094	→HMS
095	PRTX
096	SPC
097	SPC
098	SPC
099	SPC
100	SPC
101	RTN
102	R/S